PHYS 393
Low Temperature Physics
Set 7:

Low Temperature: Cooling Techniques

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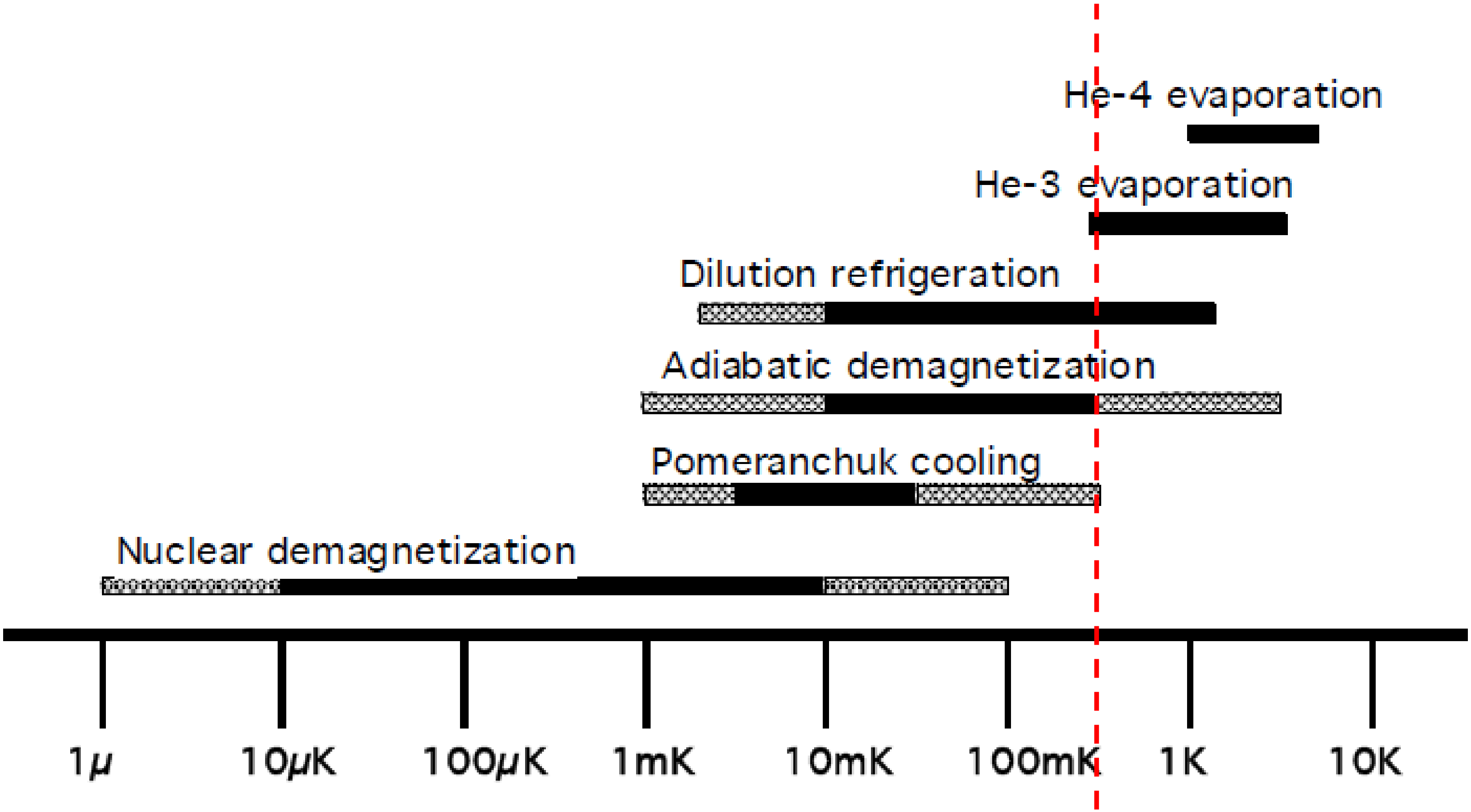
Gas liquefaction and refrigeration

- Standard cooling technique for 300<T<4.2K: cryogenic liquids (Nitrogen, Helium) obtained from liquefaction
- Oxygen liquefaction: 1877
- Helium liquefaction: 1908
- Varying vapour pressure over He^3 bath allows to maintain down to 0.3K

Substance	T_b/K
CO_2	195
CH_4	112
O_2	90.2
N_2	77.4
H_2	20.3
^4He	4.21
^3He	3.19

Boiling temperatures at atmospheric pressure

Temperature and Cooling Methods

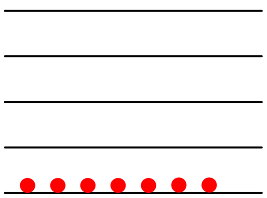


Temperature, Energy, Entropy

- Temperature T usually related to Energy U
- At low temperature it is more helpful to associate Temperature T to Entropy S
- Recall: Entropy $S=k \ln\Omega$
  - Ω = number of microstates of system
  - Quantitatively Ω represents the disorder in the system
- In equilibrium system as $T\rightarrow 0$ system goes to ground state $\Omega=1$ and $S=0$
  - But energy U is not 0 (ground state energy)

U, S at T=0

- System of N bosons
  - Bosons condense into ground state



$$T \to 0$$

$$U \to 0 \quad \text{(ignoring zero point energy)}$$

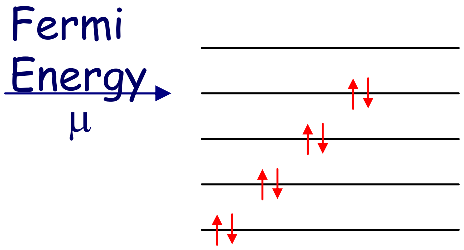
$$S \to 0$$

- System of N electrons (Fermions)
  - Electrons condense to lower set of states (Pauli principle)

$$T \to 0$$

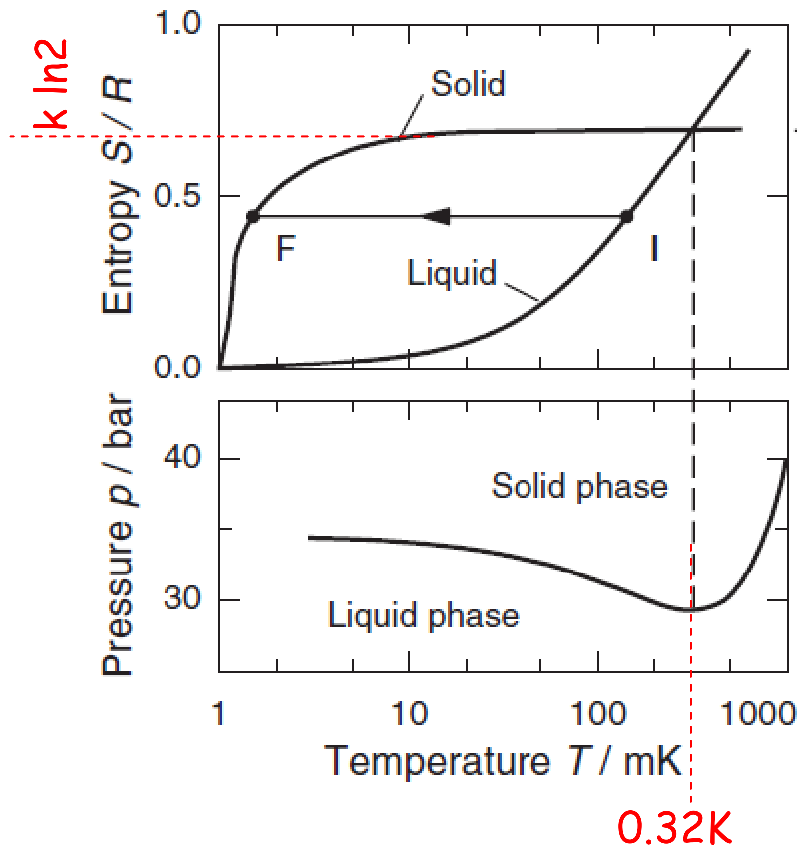
$$U \to \tfrac{3}{5} N \mu$$

$$S \to 0$$



Pomeranchuk cooling (1K to 1mK)

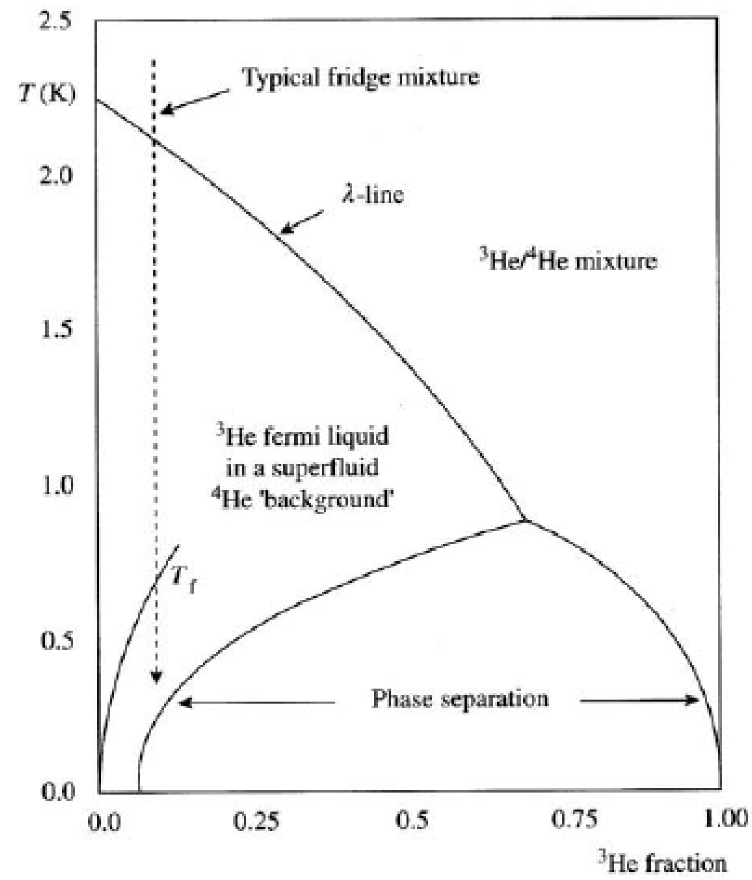
- Working substance: He^3
- 2mK<T<0.32K: entropy of liquid less than entropy of solid (Low Temperature notes 1, p. 13-16)
- Nuclear spins in solid (localized atoms) more disordered than liquid
- Compress adiabatically (I to F): temperature drop from T_I to T_F
- Takes place in thermally insulated cell
- Sample to be cooled is attached to the cell



Note logarithmic x-axis

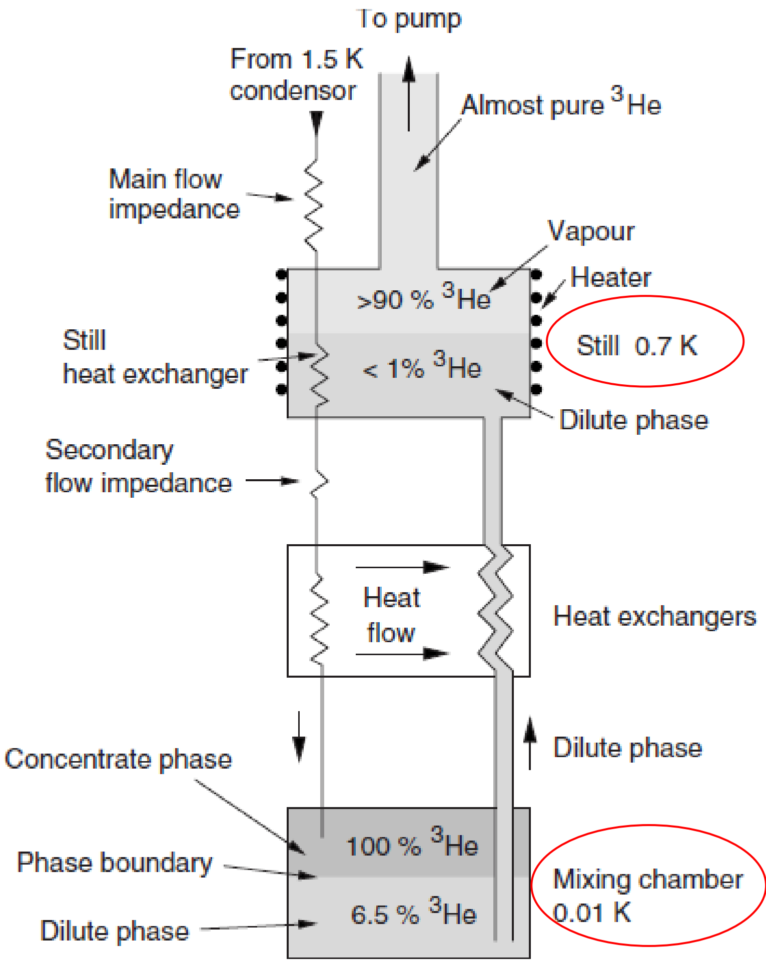
He^3/He^4 Dilution Refrigerator

- Main method to cool to ~1mK
- Phase separation below 0.86K (Low Temperature notes 5, p. 3-5): Layer of pure He^3 floats on top of layer of ~6% He^3 in He^4
- He^4 at this temperatures is 100% superfluid
- He^3 in He^4: free gas in massive vacuum
- He^3 has higher entropy in He^4 dilute phase than in pure He^3
- When He^3 crosses boundary from pure He^3 into dilute phase its entropy increases, hence it absorbs heat
- Similar to evaporation
- The trick is to make this "evaporation" happen



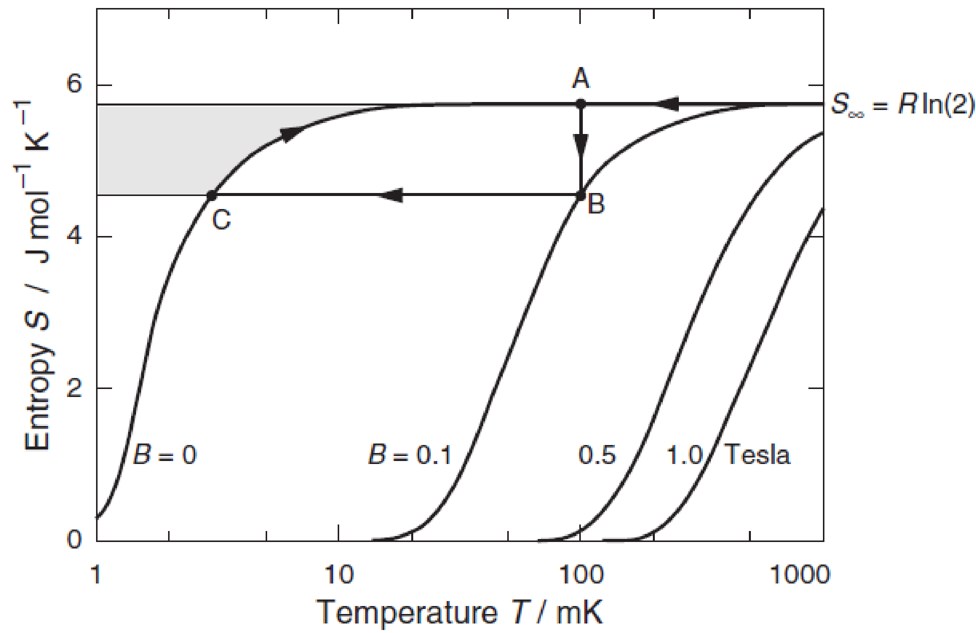
Dilution refrigerator

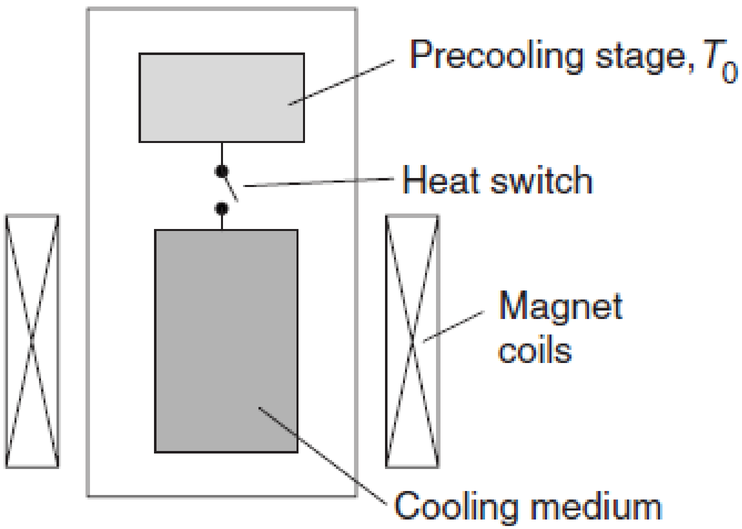
- Cooling happens in mixing chamber
- Dilute phase connected to still
- Vapour pumped out of still (preferentially He^3 due to higher vapour pressure)
- Purified
- cooled in still (0.7K)
  cooled in heat exchanger (mK)
- returned to the pure He^3 phase



Adiabatic demagnetization

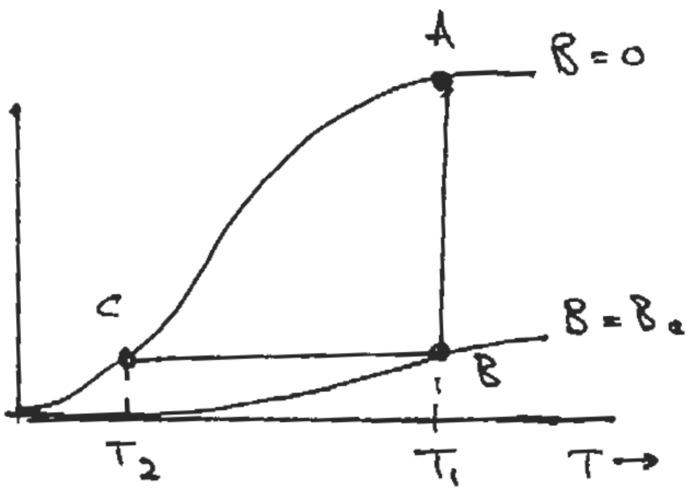
- Relies on magnetic field dependence of spin entropy
- Principle: pre-cool sample; use B field to align spins (reduces entropy releasing heat); isolate thermally, switch B field off: system cools (path ABC)
- Cooling via adiabatic demagnetization of atomic magnetic moments used since 1933
- Reaches temperatures down to 1mK

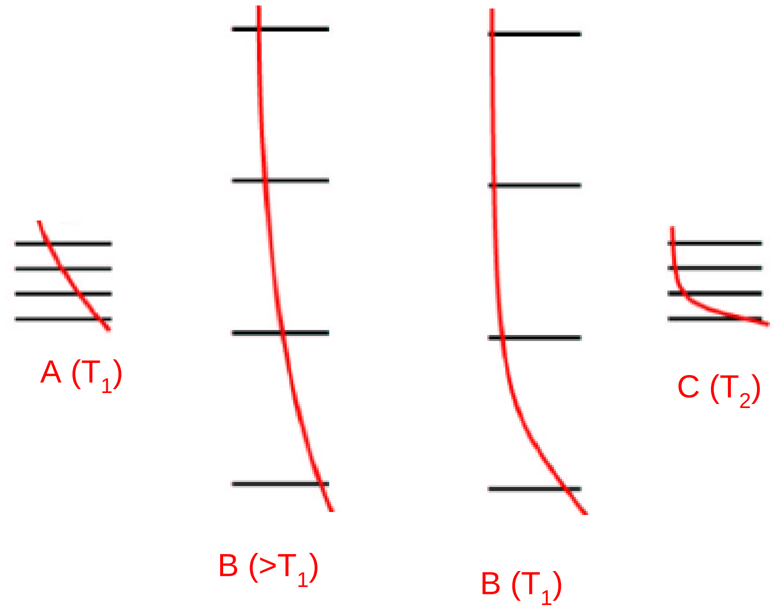




Nuclear Adiabatic Demagnetization

- Nuclear Spin Polarization: mK $\rightarrow$ μK
- Metallic copper (^{63}Cu, spin 3/2)





1. Magnetize sample isothermally at T1 (A to B) - Achieved with sample connected thermally to heat sink
2. Isolate thermally the sample
3. Demagnetize adiabatically (B to C)

A : almost degenerate states, similar populations
B (>T1) : large energy gaps, higher total energy (temperature rise)
B (T1): Large energy gaps, larger population in lower states to keep energy content constant (isothermal magnetization)
C (T2): lower energy states, population shifted to lower states compared to A, thus lower temperature